Basics of Current and Voltage Transformers

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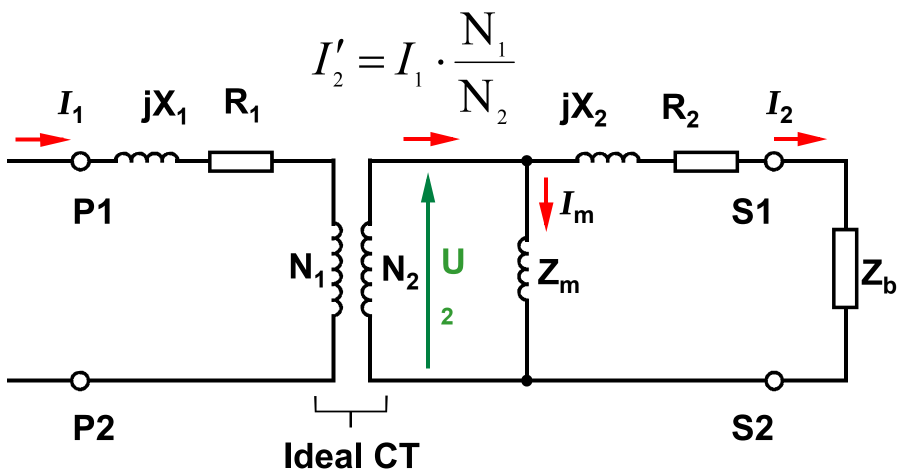
Equivalent current transformer circuit



X_1 = Primary leakage reactance
R_1 = Primary winding resistance
X_2 = Secondary leakage reactance
Z_0 = Magnetizing impedance
R_2 = Secondary winding resistance
Z_b = Secondary load

Note: Normally the leakage fluxes X_1 and X_2 can be neglected

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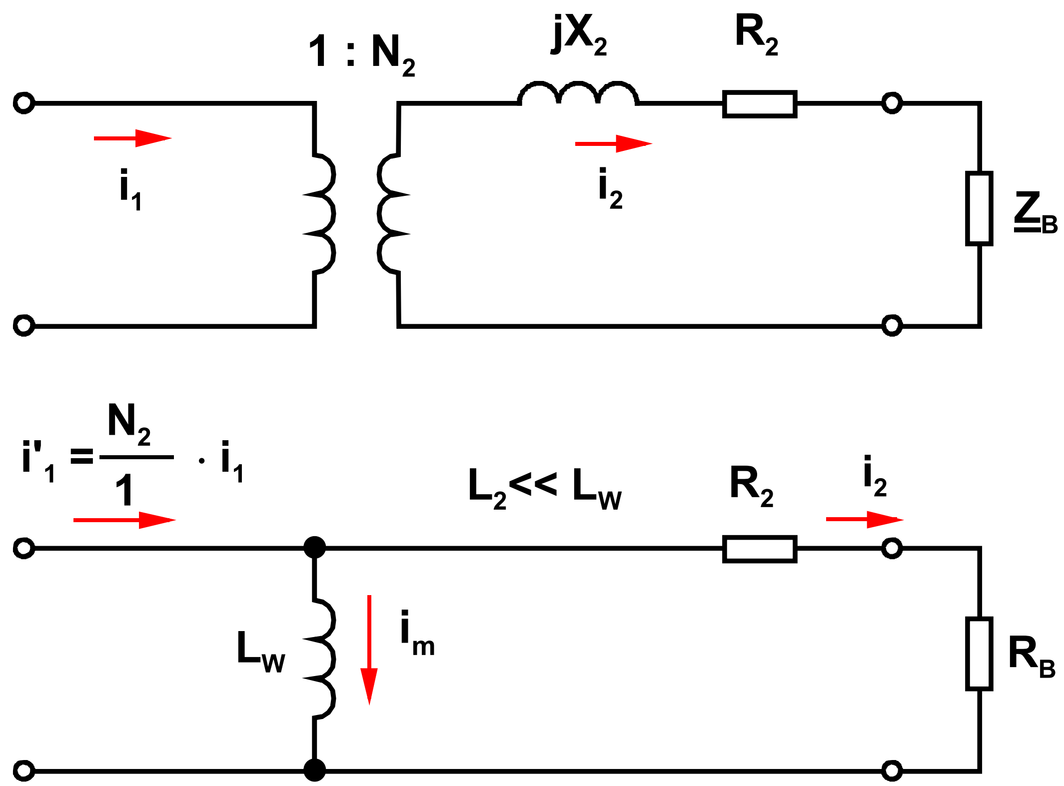
Current transformer, simplified equivalent circuit



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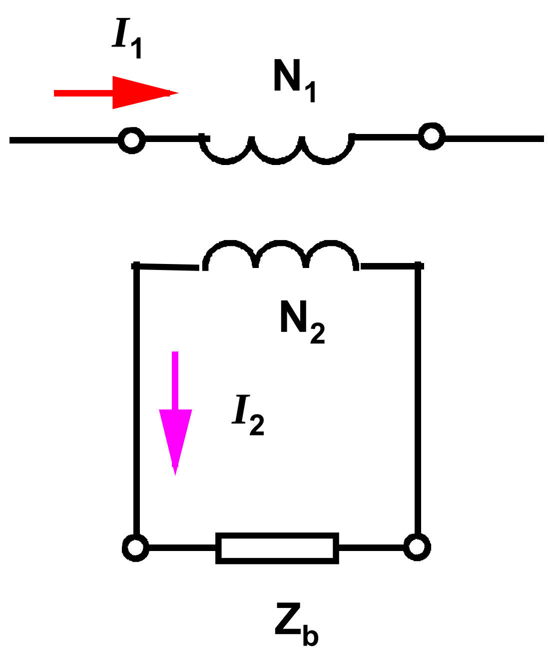
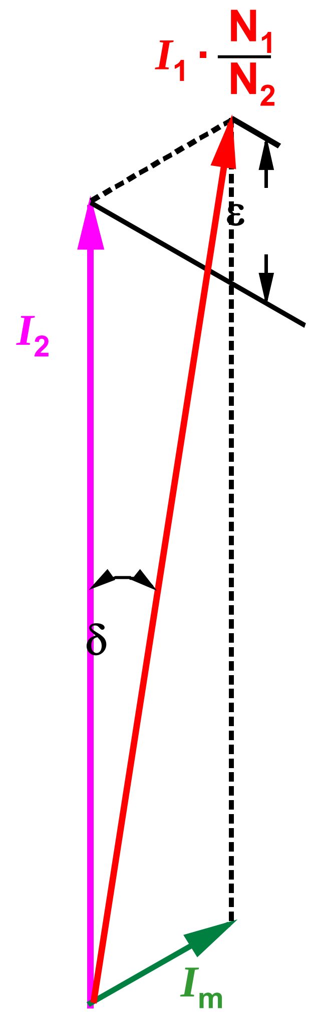
Current transformer:

Phase displacement (δ) and current ratio error (ε)





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CT classes to IEC 60044-1: 5P or 10P

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$P_i = I_{sec.}^2 \times R_{CT}$

Specification: 300/1 A 5P10, 30 VA $R_{CT} \leq 5$ Ohm

Ratio $I_{n\text{-Prim}} / I_{n\text{-Sek.}}$

5% accuracyat I= n x In

Accuracy limit factor ALF

Rated burden (nominal power) P_{NB}

Actual accuracy limit factor in operation is higher as the CT is normally underburdened :
Operating ALF: ALF‘

$$ALF' = ALF \times \frac{P_i + P_{NB}}{P_i + P_{BB}}$$

Dimension criterium:

$$ALF' \geq \frac{I_{SC-\max}}{I_n} \times K_{TF}$$

K_{TF} (over-dimensioning factor) considers the single sided CT over-magnetising due to the d.c. component in short circuit current I_{SC}.
K_{TF} values required in practice depend on relay type and design.
Recommendations are provided by manufacturers (see Application Guides)

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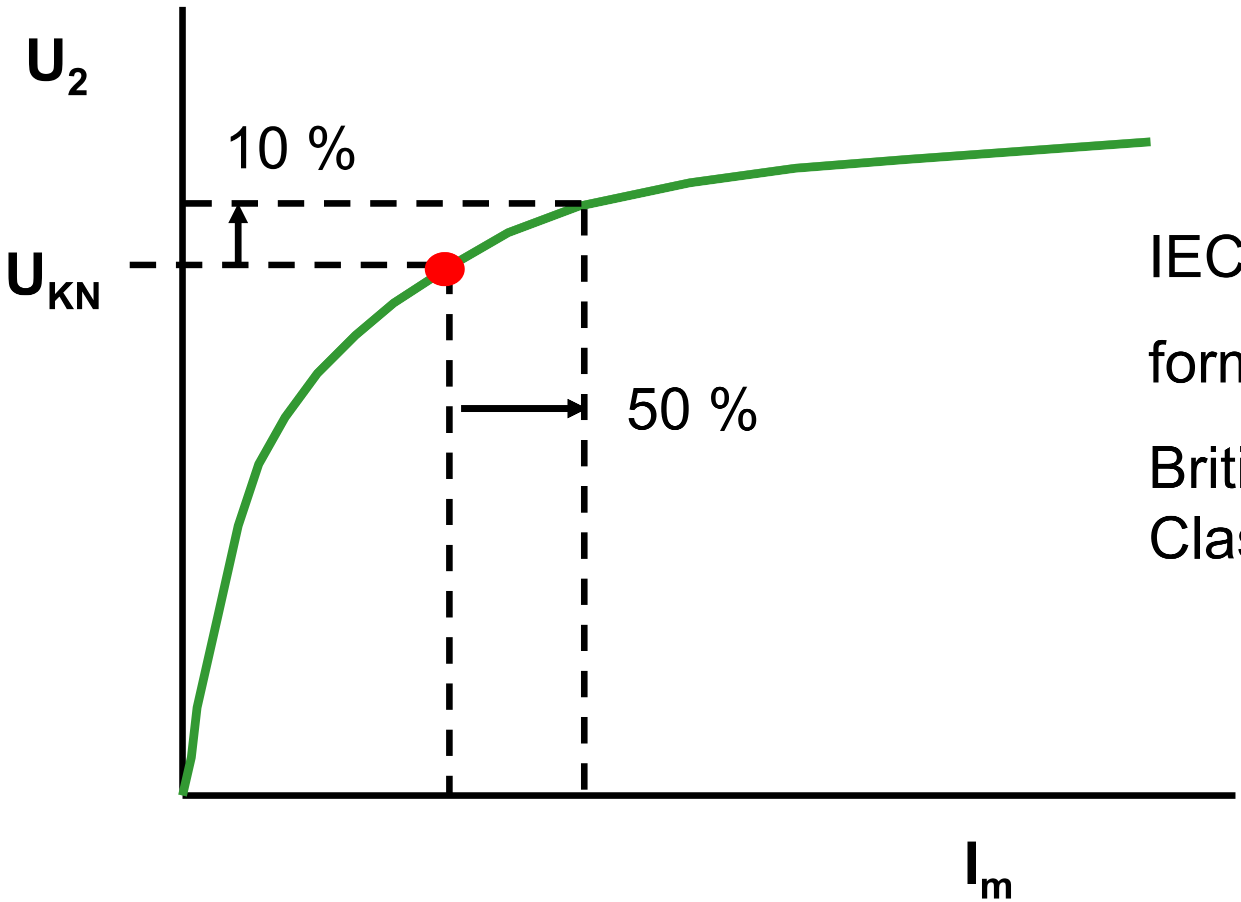
Definition of the CT knee-point voltage



IEC 60044-1 Class PX

formerly

British Standard BS3938:
Class X

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Current transformer, Standard for steady-state performance

IEC 60044-1 specifies the following classes:

Accuracy class	Current error at nominal current (In)	Angle error δ at rated current In	Total error at n x In (rated accuracy limit)
5P	± 1 %	± 60 minutes	5 %
10P	± 5%	———	10 %

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Current transformers, Standard for transient performance

IEC 60044-6 specifies four classes:

Class	Error at rated current		Maximum error at rated accuracy limit	Remanence
	Ratio error	Angle error		
TPX (closed iron core)	± 0,5 %	± 30 min	$\hat{\varepsilon} \leq 10\%$	no limit
TPY with anti-remanence air gap	± 1,0 %	± 30 min	$\hat{\varepsilon} \leq 10\%$	< 10 %
TPZ linear core	± 1,0 %	± 180 ± 18 min	$\hat{\varepsilon} \leq 10\%$ (a.c. current only)	negligible
TPS closed iron core	Special version for high impedance protection (Knee point voltage, internal secondary resistance)			No limit

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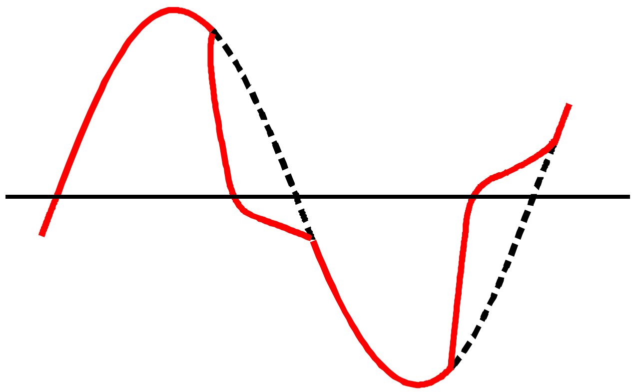
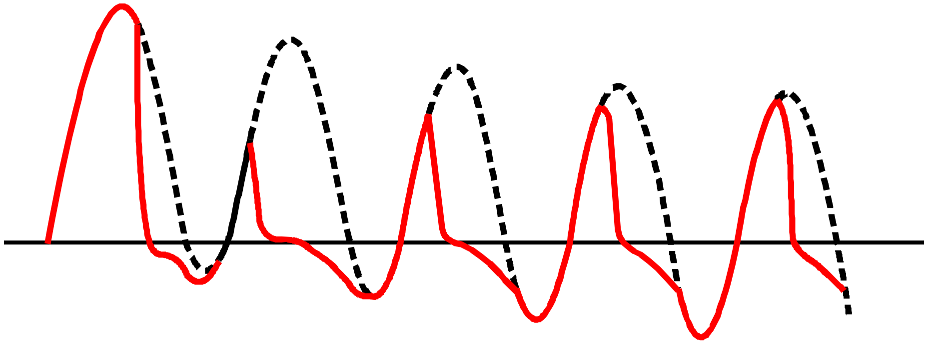
Current transformer saturation



Steady-state saturation with AC current



Transient saturation with offset current

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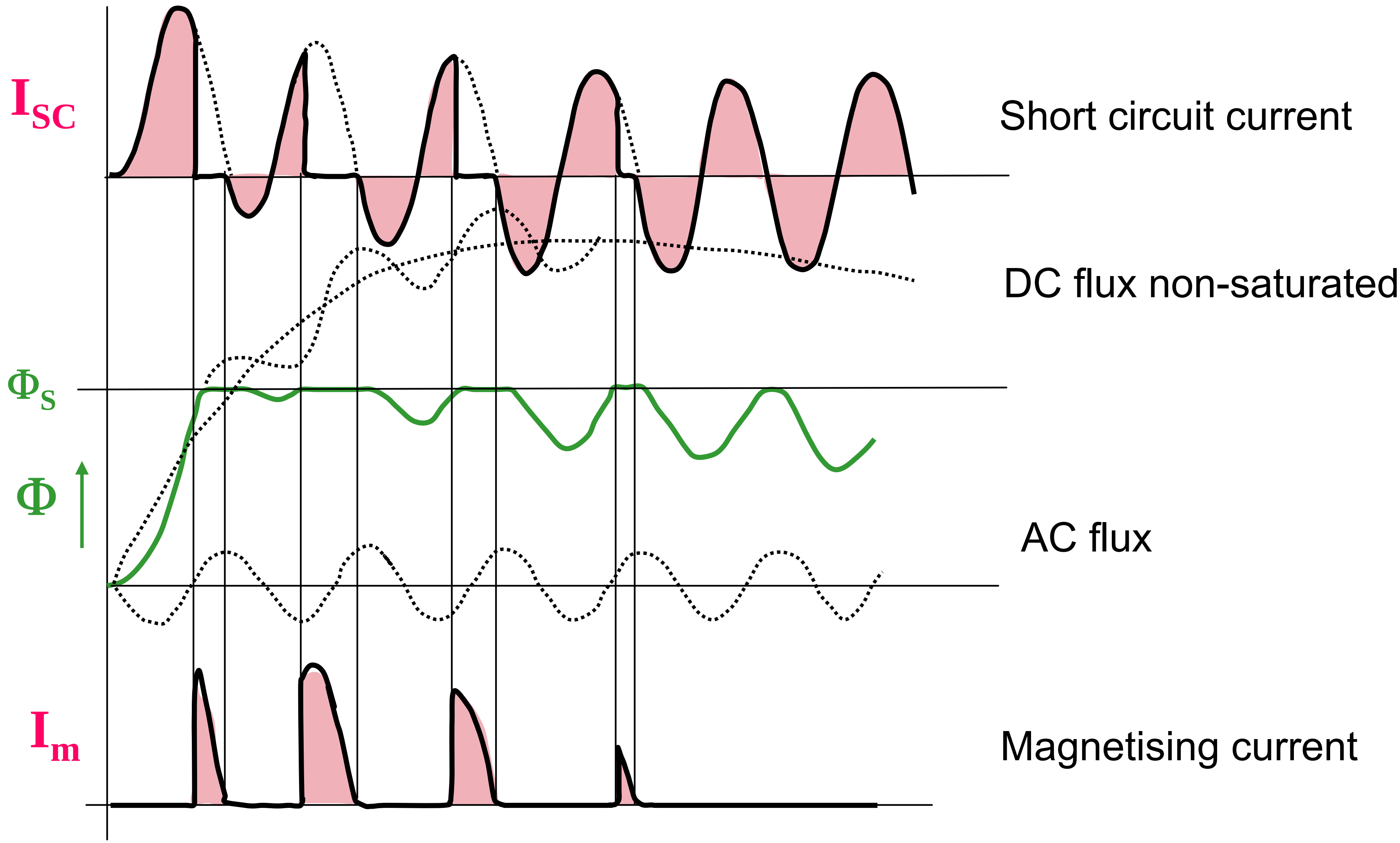
Transient CT saturation due to DC component



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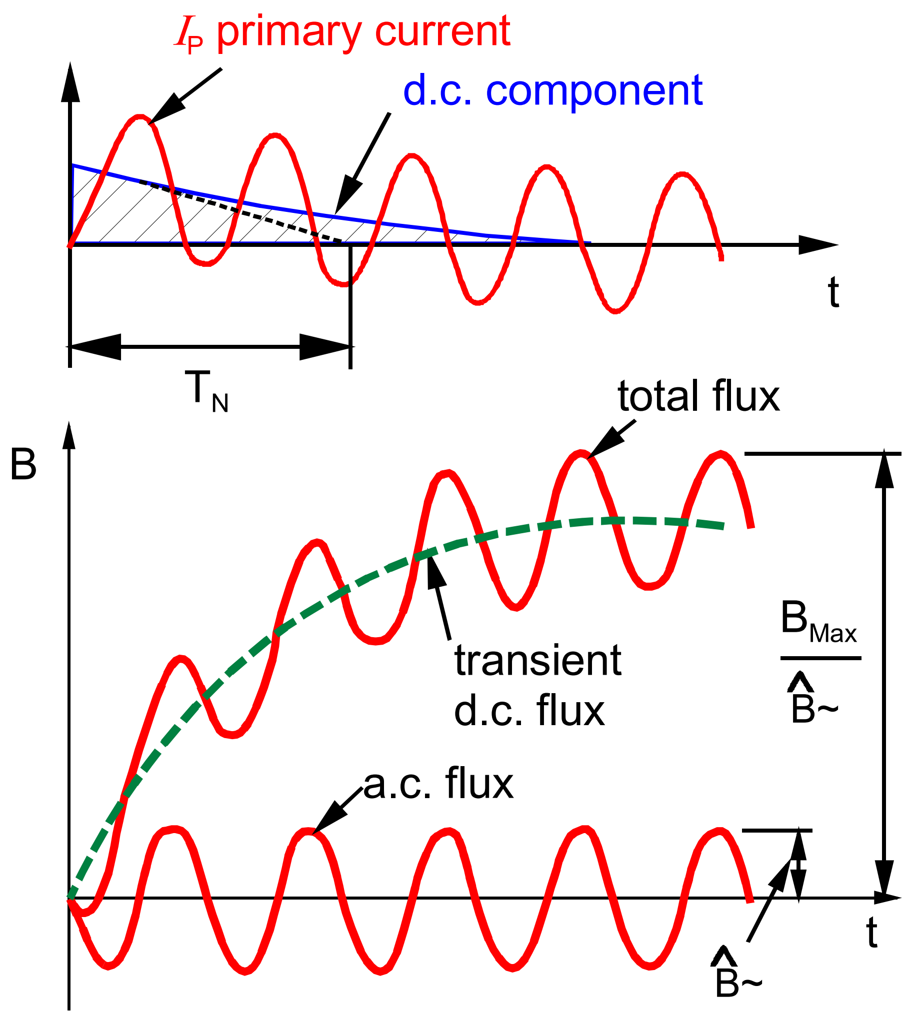
Course of CT-flux during off-set short-circuit current



$$\frac{B}{\hat{B}_\sim} = 1 + \frac{\omega \cdot T_N \cdot T_S}{T_N - T_S}\left(e^{-\frac{t}{TN}} - e^{-\frac{t}{TS}}\right)$$

$$\frac{B_{Max}}{B\sim} = 1 + \omega \cdot T_S \cdot \left(\frac{T_N}{T_S}\right)^{\frac{TS}{TS-TN}}$$

$$t_{B\,Max} = \frac{T_N \cdot T_S}{T_S - T_N} \cdot \ln\frac{T_S}{T_N}$$

$$T_S = \frac{L_W}{R_i + R_B} = \frac{1}{\omega \cdot \tan\delta}$$

For 50 Hz: $T_S = \frac{10900}{\delta_{[min]}}$ [ms]

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CT transient over-dimensioning factor K_{TF}

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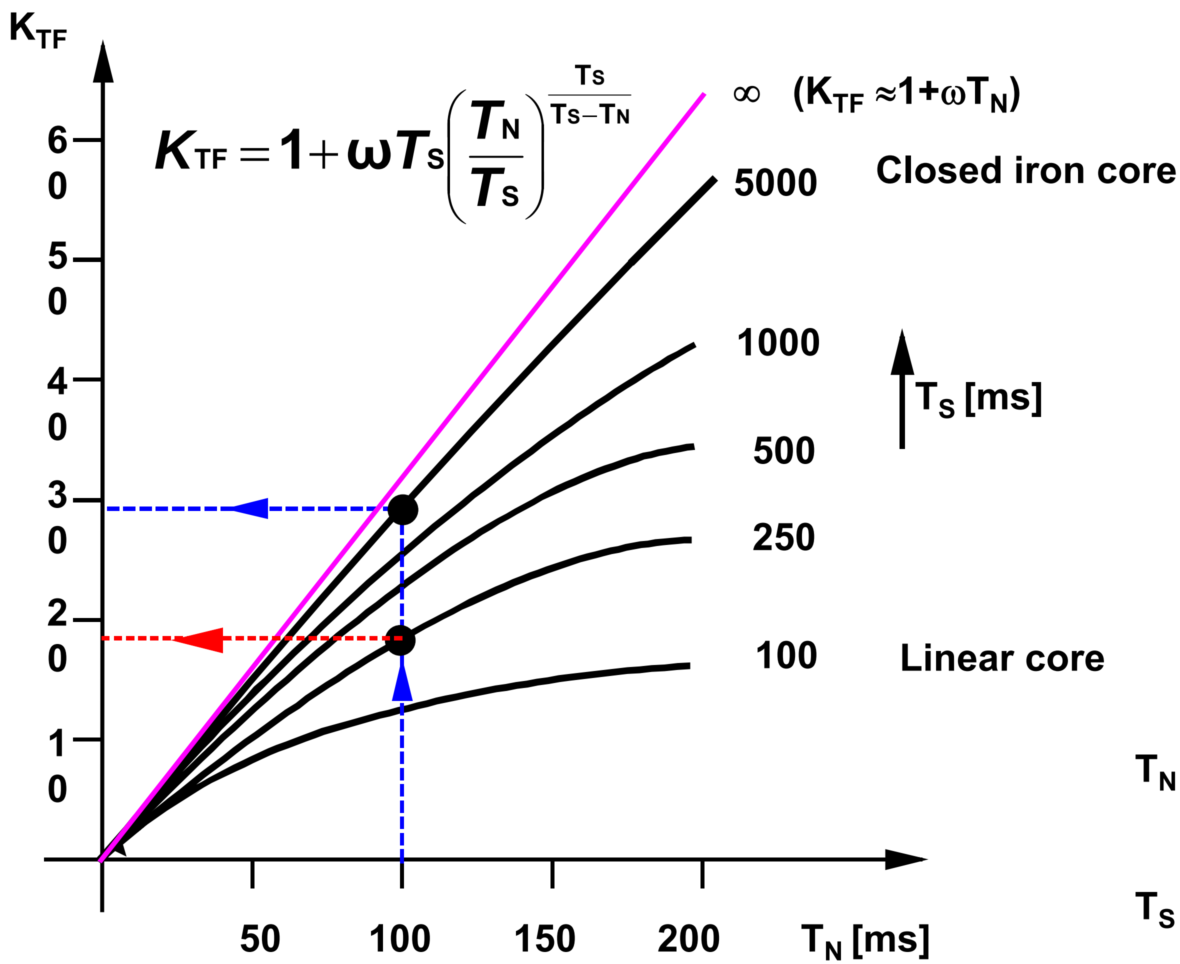

T_N = network time constant (short-circuit time constant)

T_S = CT secondary time constant

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CT with closed iron core, Over-dimensioning factor K_{TF}‘ for specified time to saturation (t_M)

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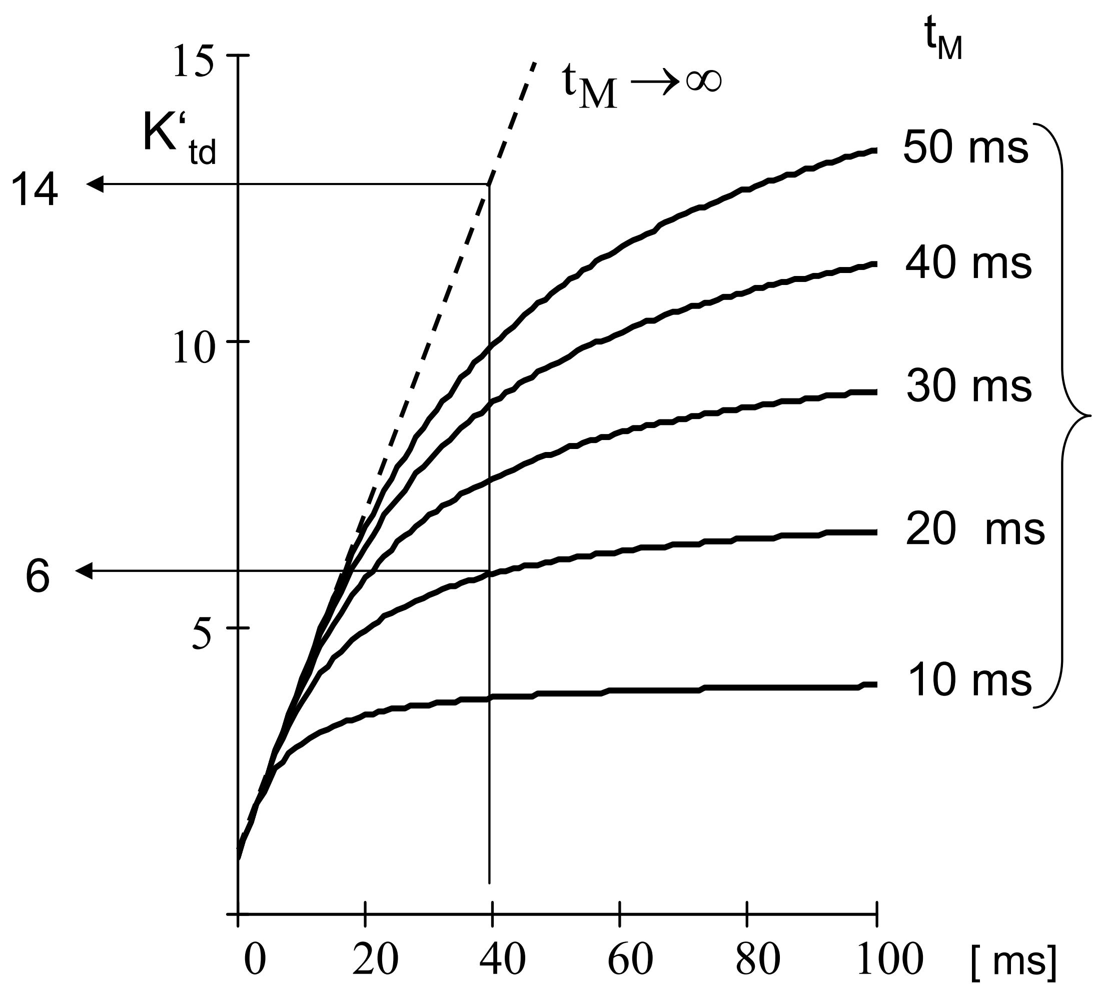

$$K'_{TF} = 1 + \omega T N \cdot \left(1 - e^{-\frac{t_M}{T_N}}\right)$$

$t_M \to \infty$:

$$K_{TF} = 1 + \omega T_N = 1 + \frac{X_N}{R_N}$$

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CT over-dimensioning factor K_{TF} (t_M,T_N) in the case of short time to saturation (t_M)

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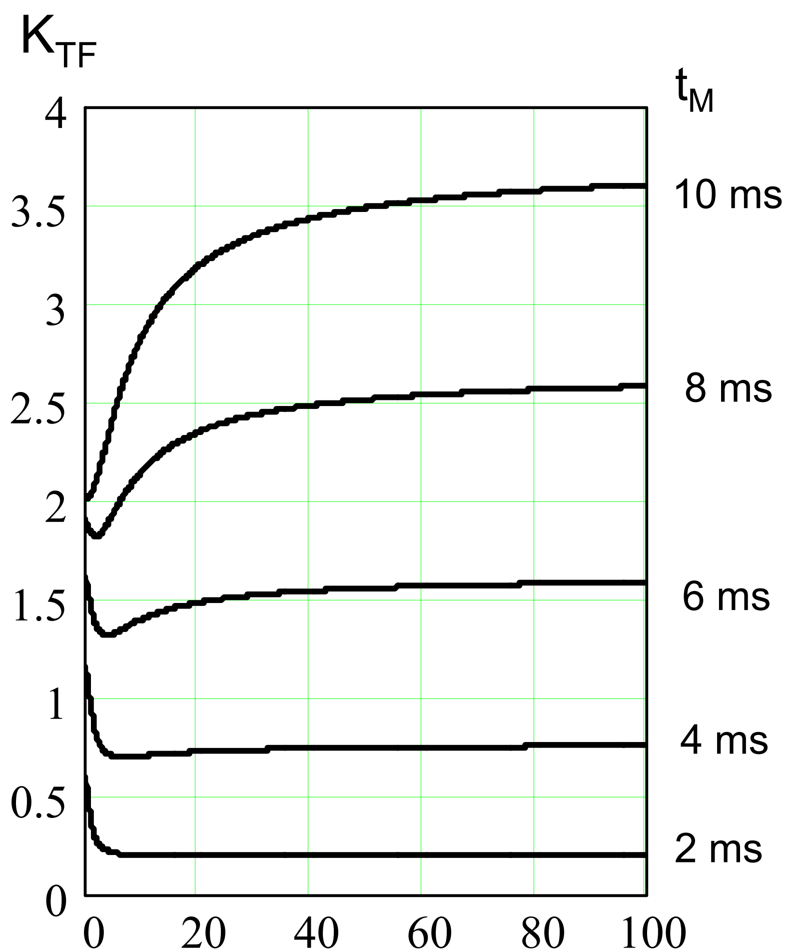
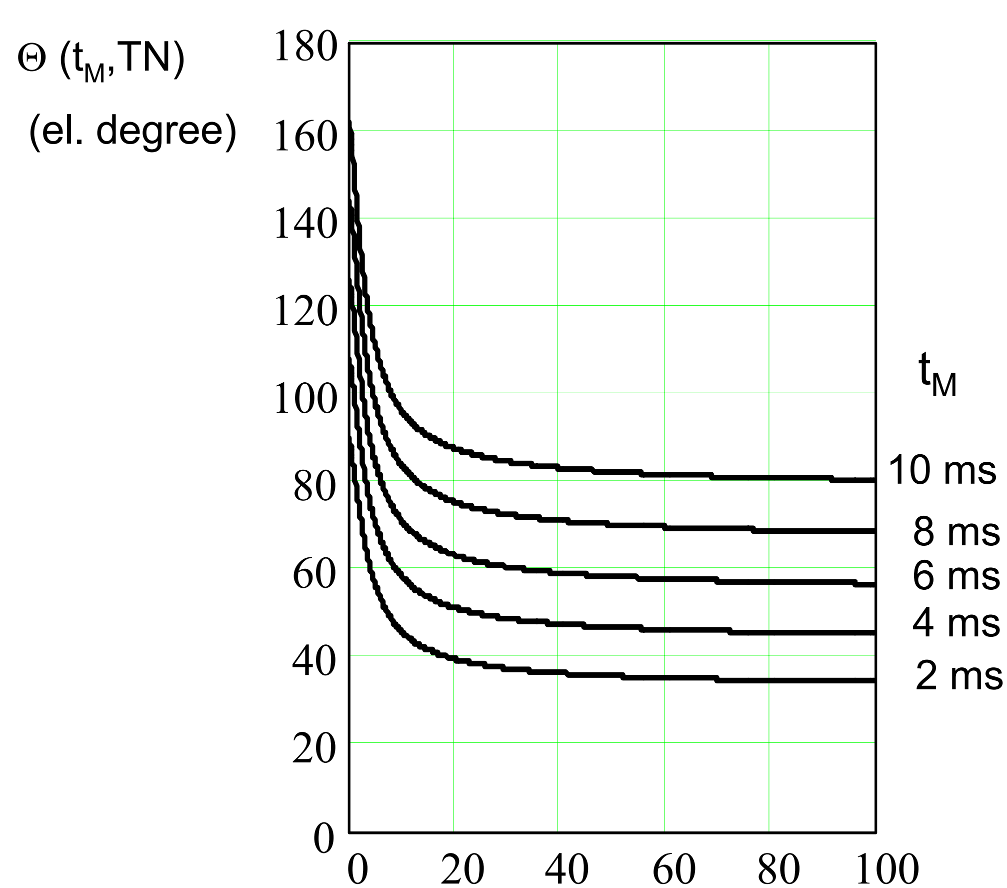
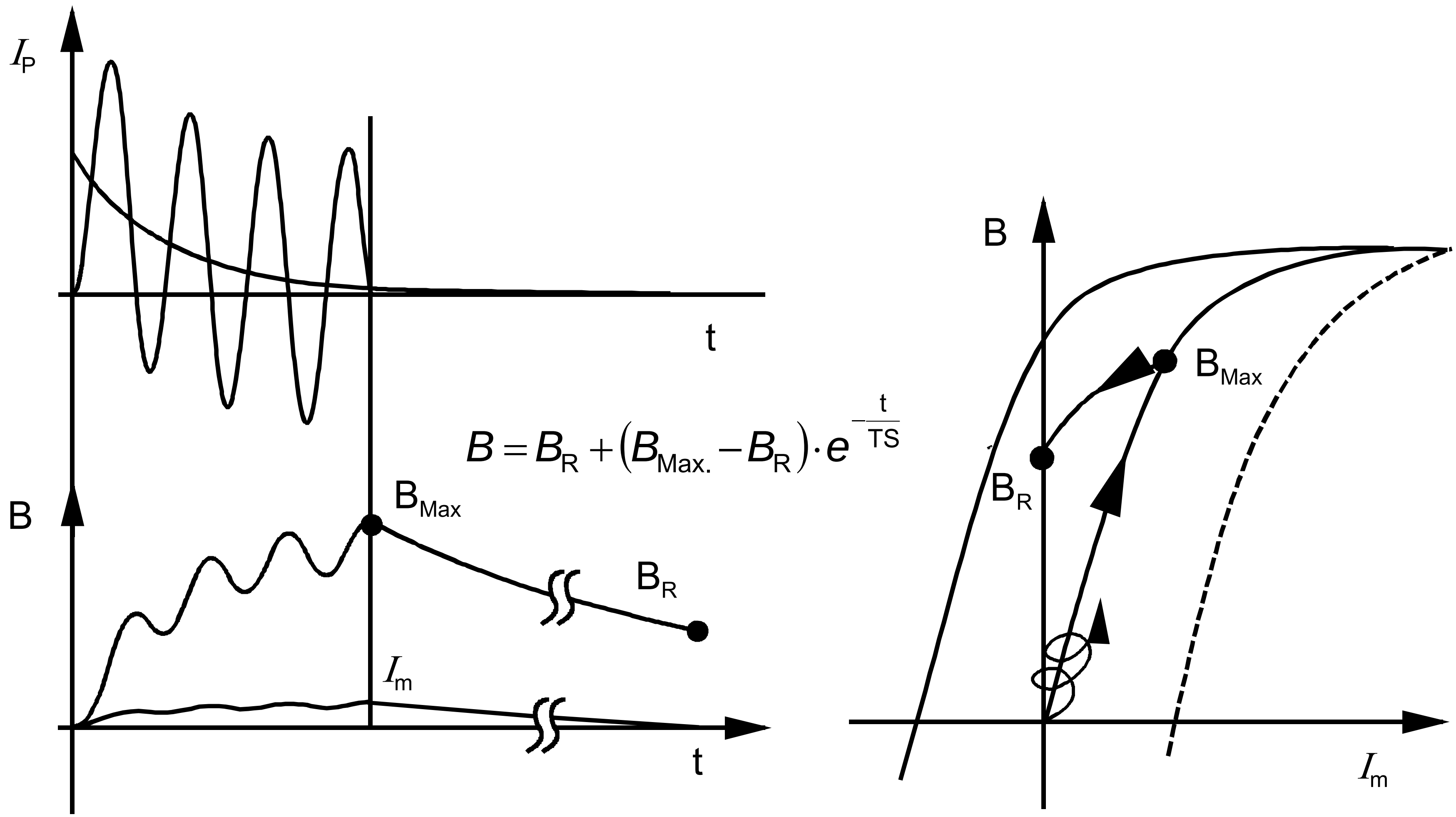




Current transformer
magnetising and de-magnetising



$$B = B_R + \left(B_{Max.} - B_R\right) \cdot e^{-\frac{t}{TS}}$$

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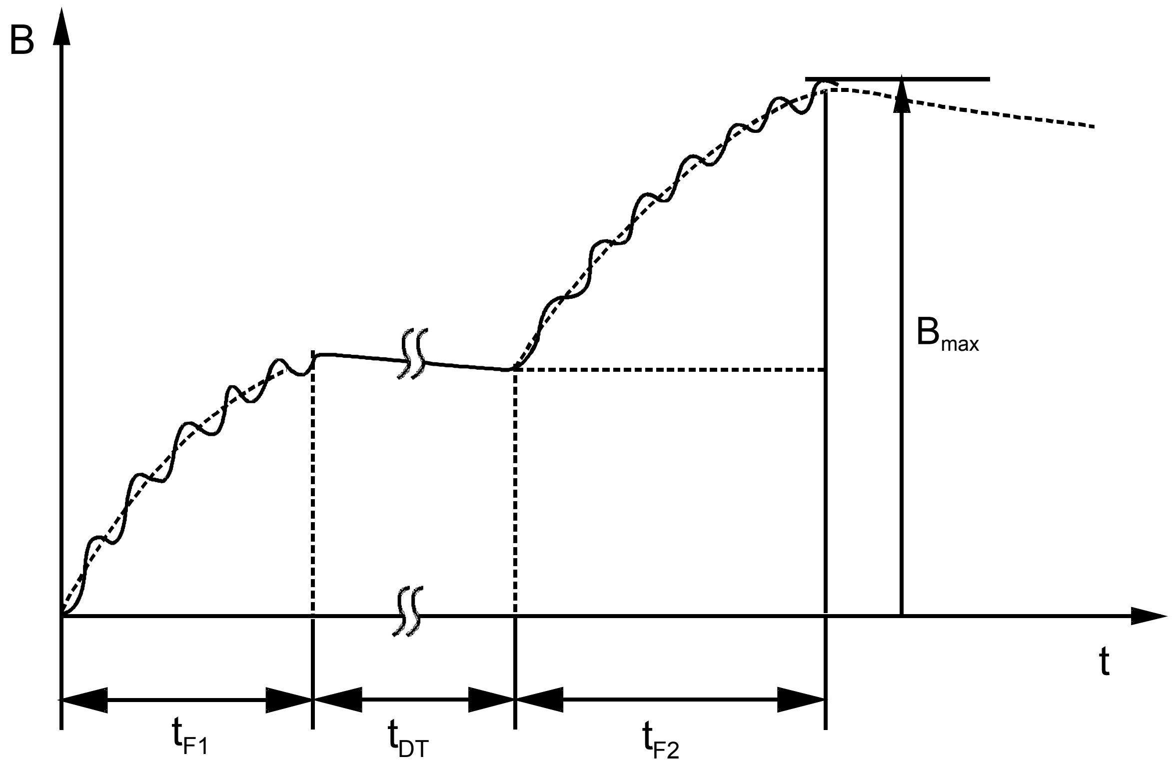
Course of flux in the case of non-successful auto-reclosure



t_{F1} = duration of 1st fault

t_{DT} dead time

t_{F2} =duration of 2nd fault

$$\frac{B_{max}}{\hat{B}_{\sim}} = \left[1 + \frac{\omega \cdot T_N \cdot T_S}{T_N - T_S} \left(e^{-\frac{t_{F1}}{T_N}} - e^{-\frac{t_{F1}}{T_S}}\right.\right] \cdot e^{-\frac{t_{DT}+t_{F2}}{T_S}} + \left[1 + \frac{\omega \cdot T_N \cdot T_S}{T_N - T_S} \left(e^{-\frac{t_{F2}}{T_N}} - e^{-\frac{t_{F2}}{T_S}}\right.\right]$$

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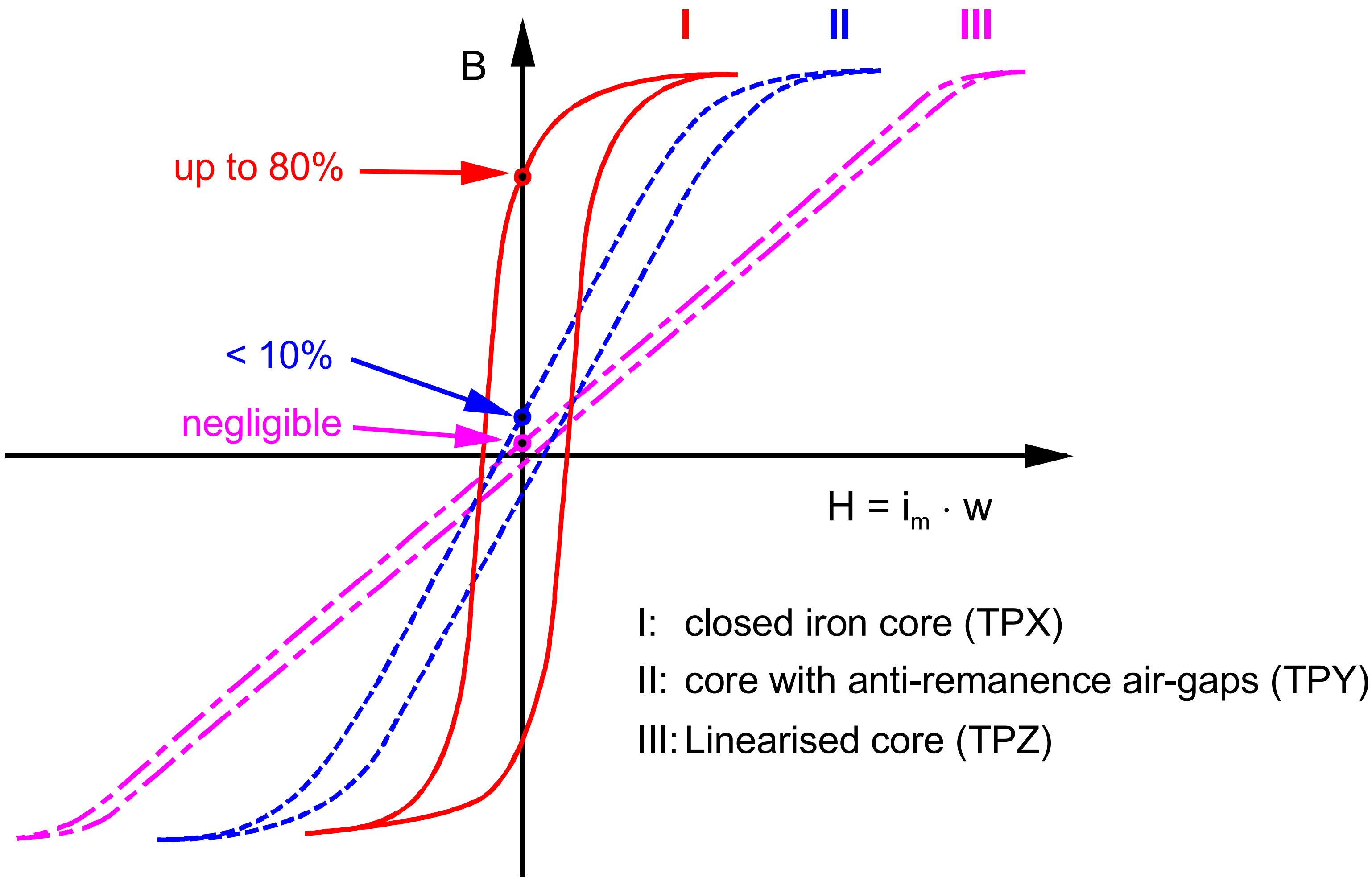
Current transformer
magnetising curve and point of remanence



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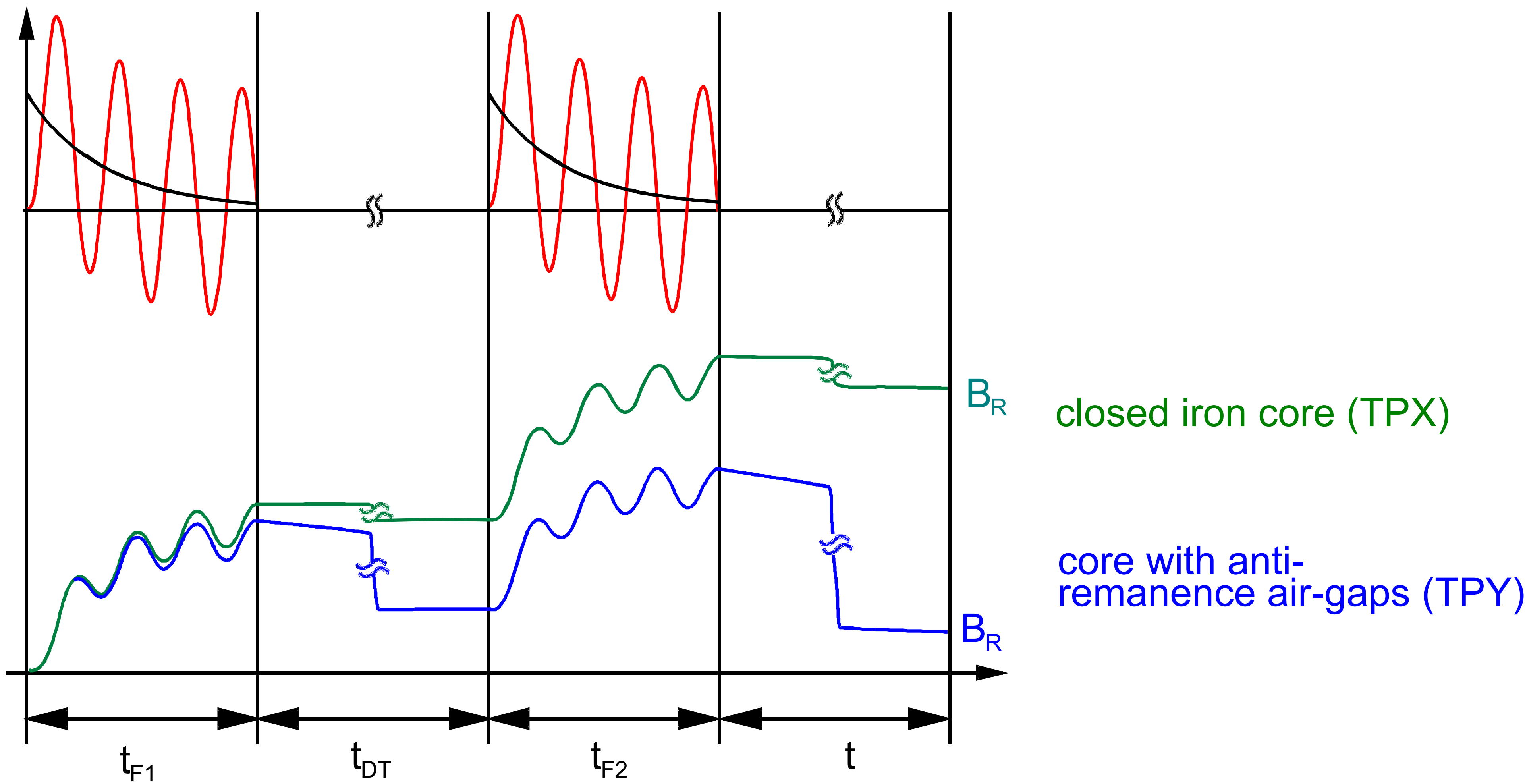
Current transformers TPX und TPY
Course of the flux with non-successful auto-reclosure



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Standards of voltage transformers

VT classes to IEC 60044-2

Class designation	Permissible error at $0.05 \cdot U_N$ and $1.0 \cdot U_N$	
	Voltage error F_U	Angle error δ
3P	± 3.0 %	120 minutes
5P	± 6.0 %	240 minutes

All 3P and 5P protection CTs must additionally comply with one of the below VT metering classes!

VT classes for measurement IEC 60044-2

Class designation	Permissible voltage error in % at $1.0 \cdot U_N$	Permissible angle error in minutes at $1.0 \cdot U_N$
0.1	0.1	5
0.2	0.2	10
0.5	0.5	20
1	1	30
3	3	Not determined

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Capacitive voltage transformer,
Equivalent circuit

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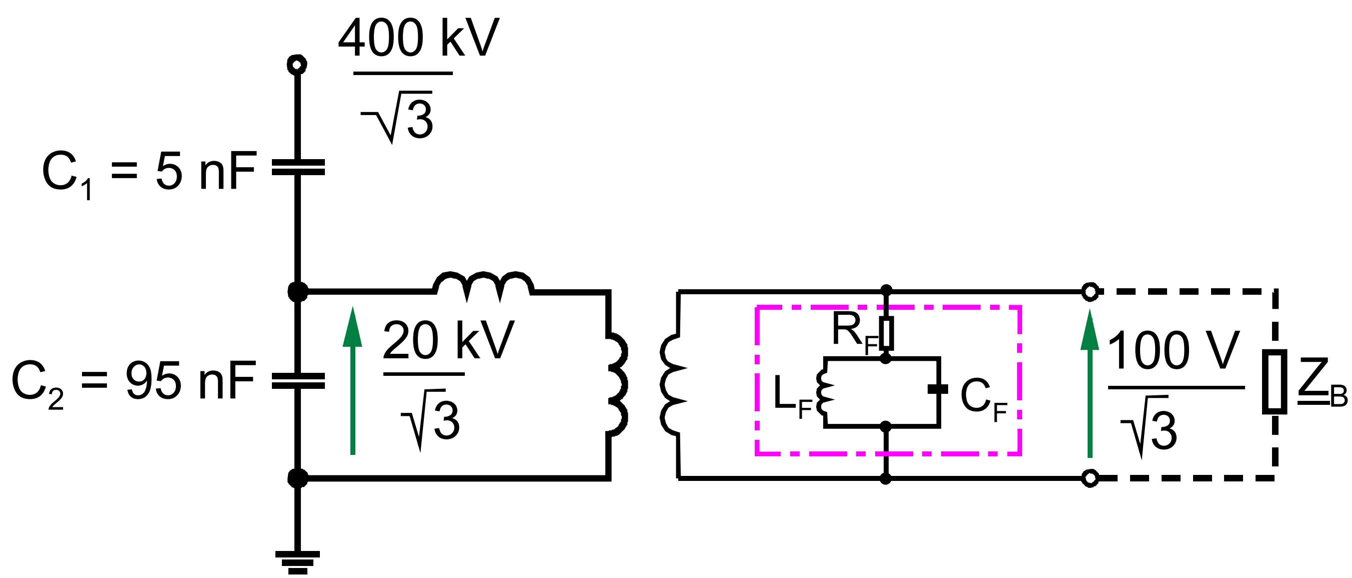

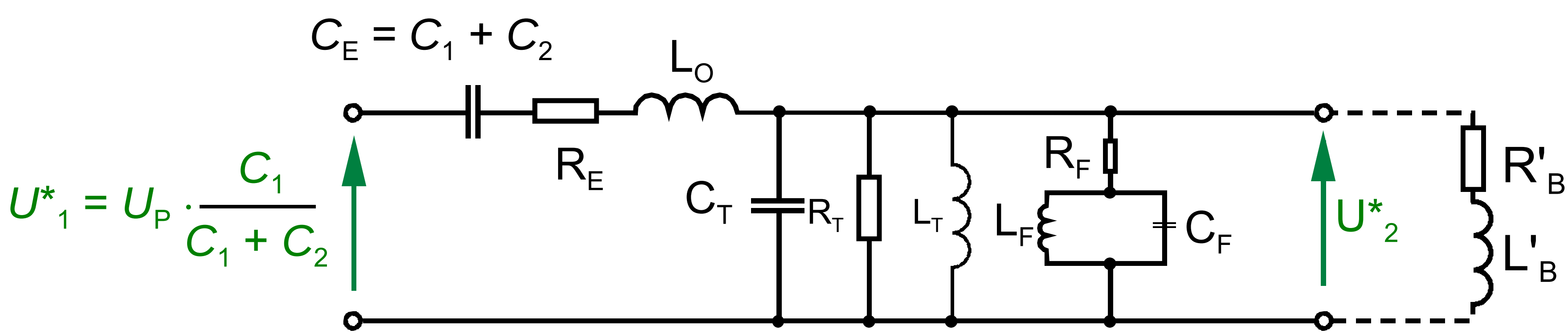

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Transient performance of CVTs, Recommendations acc. to IEC 60044-5

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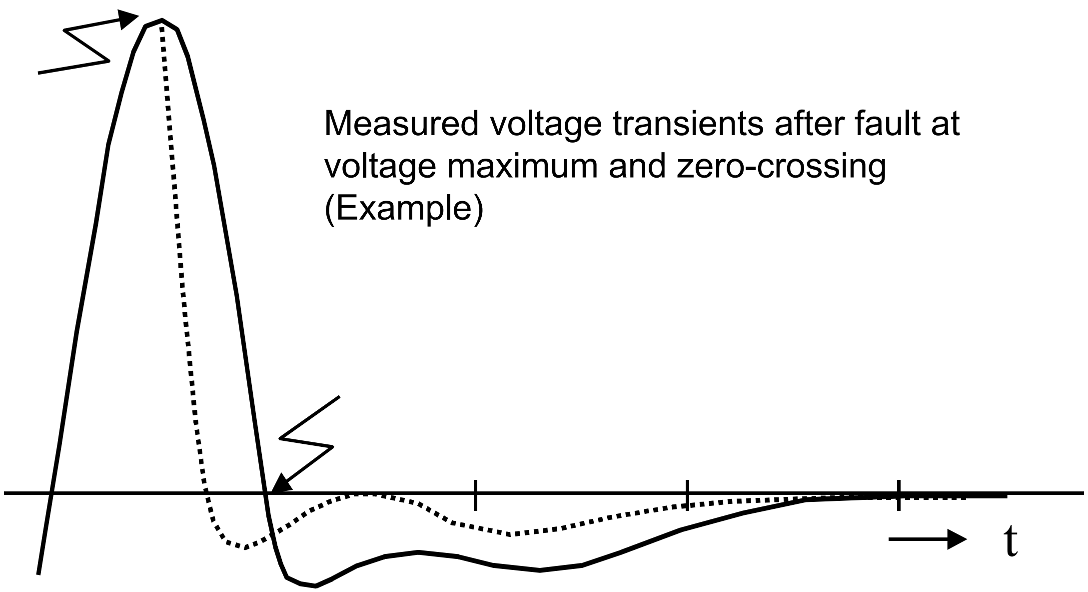

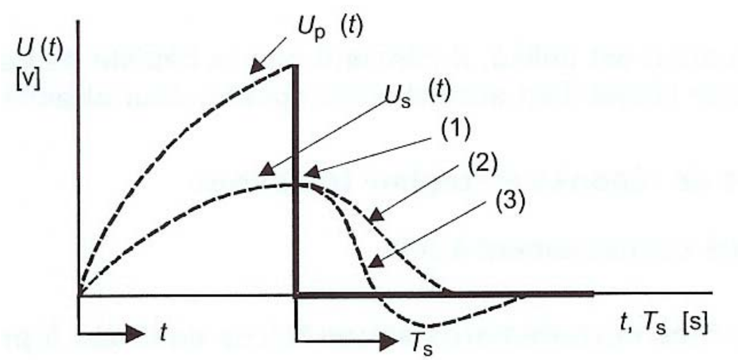

Legend:

$U_P(t)$ Primary voltage

$U_S(t)$ Secondary voltage

(1) Fault inception

(2) Aperiodic damping of $U_S(t)$

(3) Periodic damping of $U_S(t)$

Time Ts in ms	Ratio $\frac{U_S(t)}{\sqrt{2} \cdot U_S} \cdot 100\%$		
	Classes		
	3PT1 6PT1	3PT2 6PT2	3PT3 6PT3
10	---	≤ 25	≤ 4
20	≤ 10	≤ 10	≤ 2
40	≤ 10	≤ 2	≤ 2
60	≤ 10	≤ 0.6	≤ 2
90	≤ 10	≤ 0.2	≤ 2

Recommendations to IEC 60044-5

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CT dimensioning

$$K_{OD} = K_{TF}$$

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$$ALF' = ALF \cdot \frac{P_i + P_{BN}}{P_i + P_B} = ALF \cdot \frac{R_{CT} + R_{BN}}{R_{CT} + R_B}$$

rated CT burden: P_{BN}
internal burden of the CT: $P_i = R_i \cdot I_{2N}^2$

$$ALF = ALF' \cdot \frac{P_i + P_B}{P_i + P_{BN}} = ALF' \cdot \frac{R_{CT} + R_B}{R_{CT} + R_{BN}}$$

Actual connected burden : $P_B = R_B \cdot I_{2N}^2$

$R_B = R_l + R_R$ = burden resistance
R_l = resistance of connecting cables
R_R = burden resistance of the relay

with $ALF' \geq K_{OD} \cdot \frac{I_K}{I_N}$

$$K_{OD} \geq K_{TF} \cdot K_{Rem}$$

$$K_{Rem} = \frac{1}{1 - \frac{\%\,Remanence}{100}}$$

Theory:

No saturation for the total short-circuit duration: $K'_{TF} = \frac{B_{Max}}{\hat{B}_{\sim}} = 1 + \omega T_N = 1 + \frac{X_N}{R_N}$

No saturation for the specified time t_M: $K''_{TF} = \left[1 + \frac{\omega \cdot T_N \cdot T_S}{T_N - T_S}\left(e^{-\frac{t_M}{T_N}} - e^{-\frac{t_M}{T_S}}\right)\right]$

Practice:

Remanence only considered in extra high voltage systems (EHV)
K_{TF}-values acc. to relay manufacturers‘ guides

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Practical CT requirements
Transient over-dimensioning factors K_{TF} (AR not considered)

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	Close-in fault:	Fault atbalance point:
Distance 7SA6 and 7SA522	$K_{TF} \geq 5$	$K_{TF} \geq 2 \quad (\geq 1 \text{ if } T_N < 30ms)$

Overcurrent
7SJ56

ALF'≥ $I>>_{setting}/ I_N$, at least 20

	Internal fault	External fault
Transformer Differential 7UT6	KTF≥ 0.75 (Saturation free time ≥ 4 ms)	KTF≥ 1.2 (Saturation free time ≥ 5 ms)
Line differential 7SD61	KTF≥ 0.5 (Saturation free time ≥ 3 ms)	KTF≥ 1.2 (Saturation free time ≥ 5 ms)
Bus differential 7SS52	KTF≥ 0.5 (Saturation free time ≥ 3 ms)	KTF≥ 0.5 (Saturation free time ≥ 3 ms)

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CT dimensioning for Example differential protection (1)

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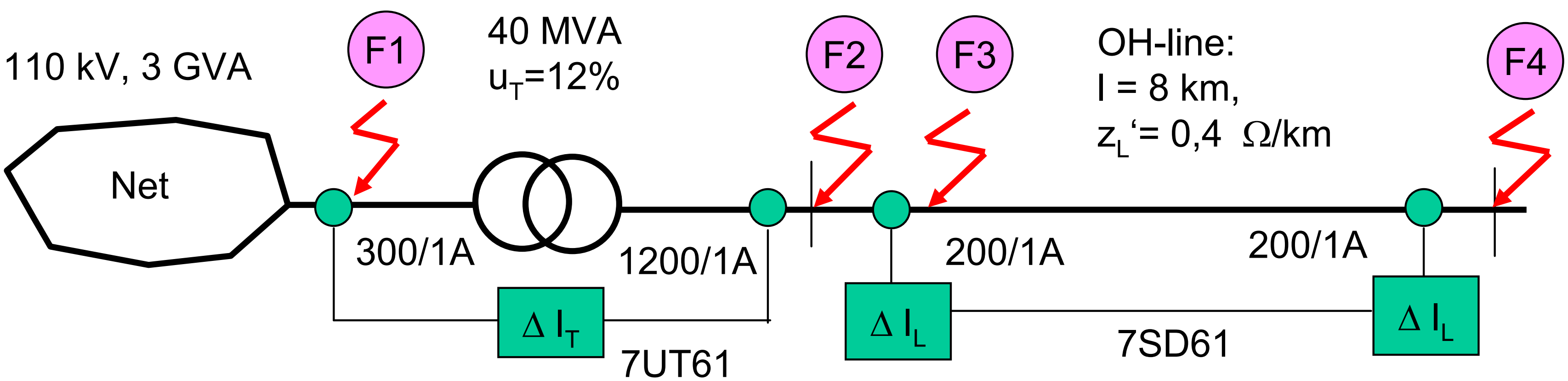
1. Calculation of fault currents



Impedances related to 110 kV:

$$\text{Net}: \quad Z_N = \frac{U_N{}^2\left[kV^2\right]}{S_{SC}''\left[MVA\right]} = \frac{110^2}{3000} = 4.03\ \Omega$$

$$\text{Transf.}: \quad Z_T = \frac{U_N{}^2\left[kV^2\right]}{P_{N\text{-}T}\left[MVA\right]} \cdot \frac{u_T[\%]}{100} = \frac{110^2}{40} \cdot \frac{12\%}{100} = 36.3\ \Omega$$

Impedances related to 20 kV:

$$\text{Net}: \quad Z_N = \frac{U_N{}^2\left[kV^2\right]}{S_{SC}''\left[MVA\right]} = \frac{20^2}{3000} = 0.13\ \Omega$$

$$\text{Transf.}: \quad Z_T = \frac{U_N{}^2\left[kV^2\right]}{P_{N\text{-}T}\left[MVA\right]} \cdot \frac{u_T[\%]}{100} = \frac{20^2}{40} \cdot \frac{12\%}{100} = 1.2\ \Omega$$

$$\text{Line}: \quad Z_L = l[km] \cdot z_L'[\Omega/km] = 8 \cdot 0{,}4 = 3{,}2\ \Omega$$

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CT dimensioning for Example differential protection (2)

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F1 $$I_{F1} = \frac{1.1 \cdot U_N / \sqrt{3}}{Z_N} = \frac{1.1 \cdot 110kV / \sqrt{3}}{4.03\Omega} = 17.3\ kA$$

F2 $$I_{F2} = \frac{1.1 \cdot U_N / \sqrt{3}}{Z_N + Z_T} = \frac{1{,}1 \cdot 110kV / \sqrt{3}}{4.03\Omega + 36.3\Omega} = 1.73\ kA$$

F3 $$I_{F3} = \frac{1.1 \cdot U_N / \sqrt{3}}{Z_N + Z_T} = \frac{1.1 \cdot 20kV / \sqrt{3}}{0.13\Omega + 1.2\Omega} = 9.55\ kA$$

F4 $$I_{F4} = \frac{1.1 \cdot U_N / \sqrt{3}}{Z_N + Z_T + Z_L} = \frac{1{,}1 \cdot 20kV / \sqrt{3}}{0.13\Omega + 1.2\Omega + 3.2\Omega} = 2.8\ kA$$

Dimensioning of the 110 kV CTs for the transformer differential protection:

Manufacturer recommends for relay 7UT61:

1) Saturation free time ≥ 4ms for internal faults
2) Over-dimensioning factor K_{TF} ≥ 1,2
for through flowing currents (external faults)

The saturation free time of **3** ms
corresponds to $K_{TF} \geq 0{,}75$
See diagram, page 59

Criterion 1) therefore reads:

$$ALF' \geq K_{TF} \cdot \frac{I_{F1}}{I_N} = 0{,}75 \cdot \frac{17300}{300} = 43$$

For criterion 2) we get:

$$ALF' \geq K_{TF} \cdot \frac{I_{F2}}{I_N} = 1{,}2 \cdot \frac{1730}{300} = 7$$

The 110 kV CTs must be dimensioned according to criterion 1).

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CT dimensioning for Example differential protection (3)

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We try to use a CT type: 300/1, 10 VA, 5P?, internal burden 2 VA.

$$ALF \geq \frac{P_i + P_{operation}}{P_i + P_{rated}} \cdot ALF' = \frac{2+2.5}{2+10} \cdot 43 = 16.1$$

(Connected burden estimated to about 2.5 VA)

Chosen, with a security margin : 300 /1 A, 5P20, 10 VA, $R_2 \leq 2$ Ohm ($P_i \leq 2$VA)

Specification of the CTs at the 20 kV side of the transformer:

It is good relaying practice to choose the same dimensioning as for the CTs on the 110 kV side:

1200/1, 10 VA, 5P20, $R_2 \leq 2$ Ohm ($P_i \leq 2$VA)

Dimensioning of the 20 kV CTs for line protection:

For relay 7SD61, it is required:

1') Saturation free time ≥ 3ms for internal faults

2') Over-dimensioning factor $K_{TF} \geq 1.2$ for through flowing currents (external faults)

The saturation free time of **3** ms corresponds to $K_{TF} \geq 0.5$

See diagram, page 59

Criterion 1') therefore reads:

$$ALF' \geq K_{TF} \cdot \frac{I_{F3}}{I_N} = 0.5 \cdot \frac{9550}{200} = 24$$

For criterion 2') we get:

$$ALF' \geq K_{TF} \cdot \frac{I_{F4}}{I_N} = 1.2 \cdot \frac{2800}{200} = 16.8$$

The 20 kV line CTs must be dimensioned according to criterion 1').

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CT dimensioning for
Example differential protection (4)

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For the 20 kV line we have considered the CT type: 200/5 A, 5 VA, 5P?, internal burden ca. 1 VA

$$ALF \geq \frac{P_i + P_{operation}}{P_i + P_{rated}} \cdot ALF' = \frac{1+1}{1+5} \cdot 24 = 8$$

(Connected burden about 1 VA)

Specification of line CTs:

We choose the next higher standard accuracy limit factor ALF=10 :
Herewith, we can specify: CT Type TPX, 200/5 A, 5 VA, 5P10, $R_2 \leq$ 0.04 Ohm ($P_i \leq$ 1 VA)

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